NON-THERMAL RADIO-NOISE FROM INTERSTELLAR GRAPHITE GRAINS

by

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ABSTRACT

It is shown that interstellar graphite grains will radiate radio-noise with a dependence of intensity on frequency of $\nu^{-\alpha}$, where $0.5 < \alpha < 1$. α is a parameter depending on the grain geometry. A dipole moment is set up in a grain which is moving across the magnetic field by the associated electric field acting on carriers of the conduction band. The dipole oscillates because the grains, which are strongly anisotropic in their electrical conductivity, are rotating, the rotation being at radio frequencies when there is equipartition of angular energy between the grains and the gas. The oscillating dipole then radiates. Integration over the size distribution and the rotation distribution gives the intensity of the emitted radiation as a function of the magnetic field, the velocity through the field, the number of grains and the gas temperature. With grains in $100^{\circ}K$ interstellar clouds having a velocity component across the magnetic field of the clouds' random velocity, the observed galactic non-thermal radio-noise intensity is obtained with a magnetic field of 10^{-6} gauss. The radiation is partially polarized.

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INTRODUCTION

The non-thermal component of the galactic radio-noise was first attributed to synchrotron radiation from relativistic electrons moving through the galactic magnetic field by Kiepenhauer (1950). The synchrotron mechanism has since been refined by a number of investigators. It has become widely accepted, and is used to derive various properties of the galaxy. Woltjer (1962) derives a magnetic field intensity in the plane of the galaxy of $\sim 3 \times 10^{-5}$ gauss. Spitzer (1962) has shown that a magnetic field of this strength places a number of serious restrictions on the dynamics of the interstellar media, and that it might also produce more than the observed alignment of interstellar grains. We propose a mechanism for non-thermal galactic radio-emission which requires a magnetic field intensity that is less by an order of magnitude.

The problem of radio-emission from rotating grains was treated by Erickson (1957). He suggested that the grains might have either permanent or statistical dipole moments and that since they spin rapidly, could be considered to form rotating dipoles which then radiate. His difficulties stemmed from maintaining the rotational energy of the grains. Considerable progress has been made since then in specifying the physical properties of interstellar grains. We shall show that interstellar grains composed of graphite flakes will, under physical conditions to be expected in the interstellar media, radiate sufficient radio-energy with the observed spectral-energy distribution.

In Section II it will be shown that a graphite grain which is moving across the galactic magnetic field has an induced dipole moment which changes in magnitude and direction as the grain rotates. The expression derived for this dipole moment will then be used in Section III where the power radiated will be computed as a function of frequency for a distribution of grain sizes. In Section IV the astronomical considerations are discussed.

II. GRAPHITE GRAINS AND THEIR DIPOLE MOMENTS

Graphite is a crystal form of carbon with a distinctive structure in which the carbon atoms are chemically bound in layers of hexagon rings, these layers being stacked parallel to each other. There is only weak physical binding between the layers and so one layer may easily slide over another. However, the chemical binding between the atoms within a layer makes each layer quite strong. This anisotropy in structure is reflected in anisotropies in most other physical and chemical properties of the crystal. Most notably, the electrons in the conduction band of one layer are free to move in that layer; i.e., the resistance is low parallel to the layers; however, electrons are inhibited from flowing perpendicular to the layers by a resistance of the order of a thousand times as great as the layer resistance. This anisotropy will be seen to be essential to the mechanism discussed here.

The extinction measurements of Stecher (1965) have been interpreted (Stecher and Donn 1965) as meaning that the interstellar absorption is caused by graphite flakes, which, if treated mathematically as spheres, have a $\frac{1}{e}$th most frequent radius of 6×10^{-6} cm, and a total number density of $3 \times 10^{-11} \mathrm{cm}^{-3}$. We expect that at least some of the graphite grains will be in the form of plates so that the anisotropies will be strongly present.

We now examine the possible mechanisms for production of a dipole moment in such a graphite grain, when it is moving through the interstellar magnetic field, and rotating with angular energies given under the condition of equipartition by

$$\frac{1}{2} I \omega^2 = kT \qquad (1)$$

where ω is the angular velocity in radians per second, I is the moment of inertia about the axis of rotation, k is the Boltzman constant, and T is the temperature in ^{o}K of the gas surrounding the grain. For spherical grains of radii 10^{-5} cm, 10^{-6} cm, 3×10^{-7}cm, in a $100^{o}K$, gas, equation (1) gives angular velocities of 5×10^{5} rad. s^{-1}, 10^{8} rad. s^{-1}, and 3×10^{9} rad. s^{-1}. These angular velocities would of course be greater for flat plates of half length equal to the radius.

An electron located by vector $\underline{r}$ from the center of mass of a grain which is moving with velocity $\underline{V}$ at some unspecified angle to the galactic magnetic field $\underline{B}$ experiences an effective electric field

$$\underline{E} = \frac{1}{c}\left(\underline{V} + \underline{\omega} \times \underline{r}\right) \times \underline{B} \qquad (2)$$

due to the Lorentz forces. We shall consider only cases in which $|\underline{V}| > |\underline{\omega} \times \underline{r}|$ and concern ourselves with an electric field of $V_{\perp} B/c$, where $V_{\perp}$ is the component of the translational velocity $\underline{V}$ perpendicular to $\underline{B}$.

Three methods are apparent for the establishing of a dipole. First, we consider a grain which has an excess electron on its surface. If it is free to move on the surface then it will possess kinetic energy equivalent to the grain temperature. The electric field is not sufficient to localize the electron which may make very many transits of the grain's surface during the course of one rotation of the grain. As far as emission of radiation is concerned, the electron does not produce a dipole moment. If the electron is not free to move, then its translational motion as part of the grain merely exerts a torque which tends to cause precession of the rotation axis. The acceleration it experiences because of the rotation is small.

The second method of production of a dipole moment makes use of the anisotropy of the polarizability. The electric field $\underline{E}$ acting on the grain produces a polarization $\underline{P}$ given by

$$\underline{P} = \alpha \underline{E} \tag{3}$$

where α is the polarizability. As the grain rotates it presents to the electric field a polarizability varying between $\alpha_{\parallel}$ and $\alpha_{\perp}$, where $\alpha_{\parallel}$ is the polarizability parallel to the layers of the graphite, and $\alpha_{\perp}$ is the perpendicular polarizability. Thus, a dipole moment equivalent to $(\alpha_{\parallel} - \alpha_{\perp})\,\underline{E}$ appears and disappears as the grain rotates. This oscillating dipole will radiate energy. Making use of the principle of additivity of bond polarizabilities (see e.g. Hirschfelder, Curtiss, and Bird 1954) we estimate $\alpha_{\parallel}$ and $\alpha_{\perp}$ for our graphite grains, but find that this leads to a smaller dipole moment than one which could supply the observed radiated power.

The above discussion of the polarizability makes use of the fact that the electrons in their orbits round the carbon nuclei are perturbed, and measures the effect of the perturbation. In graphite, the π-electrons are not localized to specific carbon atoms, but form a valence band from which electrons may be transferred to the conduction band and be moved under an electric field. We now examine the effect of the electric field on the conduction band electrons and on the holes. Because of the rotation, the grain sees not the static electric field $V_{\perp}$ B/c but an alternating field. The response time of the conduction band electrons and holes (collectively known as carriers) is very short (Kittel 1956) and we regard them as obeying the field instantaneously.

When an electric field is turned on, it will, if it has a component E along the graphite crystal layers, cause the carriers to move under the force eE. However, the motion is impeded by the resistance of the grain, and a carrier velocity is attained which is proportional to E, the constant of proportionality being the mobility, μ. Due to this carrier velocity an opposing electric field is set up in the grain which, if the original field were suddenly removed, would tend to restore the grain to the original state. If the imposed field were maintained for a sufficiently long time then the carriers would drift with the velocity $\mu\{E-E(\text{induced})\}$ until the opposing induced electric field is equal to the applied field and the situation becomes static. For the situation we consider, however, the time to attain this equilibrium may be of the order of seconds which is many orders of magnitude larger than in the case where there is no resistance, i.e. the time to establish an external field.

In the case we are considering of the grains rotating with radio frequencies in an effective electric field, this field acts only for very short periods of time, $<10^{-6}$s. During this time the carriers will be displaced, but because of the limitation of the motion by the mobility the opposing field established thereby will be completely negligible compared to the applied field. This means that the applied field controls the motion of the electrons: even if the applied field is instantaneously zero, the opposing field is too weak to act appreciably on the carriers.

Let us now consider in detail what happens in the case of a rotating rod, the axis of rotation being perpendicular both to the rod and to the electric field. The carriers are presumed free to move along the length of the rod, but not perpendicular to it; so that the rod behaves with the same anisotropy as graphite. In Fig. I(a) are displayed eight positions of the rod as it rotates through a complete cycle. Whatever the distribution of carriers is in position (1), then as the rod rotates, the electric field gives a velocity to the carriers, establishing a dipole moment, this velocity increasing to a maximum at position (3) and falling to zero at position (5). There is, therefore, a maximum displacement of the carriers at position (5). The second half of the cycle serves to give the carriers an opposite velocity which returns them to their positions at the start. Therefore, to an observer situated in the grain, a dipole moment is established and destroyed during the cycle in a way depicted in Fig. I(b), (which has the same time scale as Fig. I(a)).

However, to an observer in a fixed frame of reference outside the grain the situation is not so simple. The dipole moment does indeed reach a maximum as the grain rotates, but the orientation of this dipole also changes. Fig. I(c) is meant to show how this happens. It is seen that as the radius vector from the center of the circle rotates with the grain, the intercept of the radius with the cardioid gives the relative magnitude of the dipole. We may therefore write the magnitude of the dipole moment as

$$p = \frac{1}{2} p_0 (1 - \cos \omega t). \qquad (4)$$

p_o is the maximum dipole induced in the grain relative to the situation in position (1), and is the number of pairs of carriers in the grain multiplied by the average displacement. Now since the carrier velocity at any time may be written $\mu \frac{V_\perp B}{c} \sin \omega t$ (assuming that both types of carriers-electrons and holes have the same mobilities) the displacement is

$$\mu \frac{V_\perp B}{c} \int_0^{\frac{\pi}{\omega}} \sin \omega t \, dt = 2\mu \frac{V_\perp B}{\omega c} .$$

The number density of carriers has been measured by several experimenters. In the temperature range of interest, 30°K-60°K, a value of 2×10^{18} cm^{-3} has been found by Klein (1962a) for pyrolytic graphite - a highly oriented but non-ideal graphite. We shall use this value. As has been discussed recently (Wickramasinghe, et al. 1966), there are indications from interstellar polarization data that, though small graphite grains may be rounded spherical particles, larger grains are typically flat and plate-like. It is the larger particles which will exhibit the anisotropy we desire for the process under discussion here. The plate-like grains are sometimes thought of as all having the same thickness b: however, it is likely that b is a slowly increasing function with r, the plate radius. The number of carriers per grain may then be written $2 \times 10^{18} \pi r^2 b(r)$. Even if the functional form of b(r) were known (which it is not) this number would be suspect for various reasons. First, carrier density is extremely sensitive to impurity and to crystal imperfections, and the occurrence of these faults increases with the size of the grain. Second, there is a tendency for currents to move on the surface of conductors, so that for larger grains, perhaps not all of the electrons and holes contribute to the dipole moment. In view of the evident uncertainty on this point, we shall introduce a parameter m and take the number of carriers in the grain to be $2 \times 10^{18} \pi b r^m$, where b is now a constant typical thickness of the graphite plates, and m is a number in the vicinity of 2. We then have

$$p_0 = e \,.\, 300\mu \,.\, 2\frac{V_\perp B}{c} \,.\, 10^{18} \,.\, \pi b \frac{r^m}{\omega} \qquad (5)$$

which we write as Mr^m/ω where M becomes 30 $\mu V_\perp$ Bb. The mobility which is usually quoted in practical units, not e.s.u. which we use, is multiplied x 300. It changes rapidly with impurity concentration in graphite and with disruption of the lattice structure (Klein 1962b). A high mobility, $\sim 10^5 cm^2$/volt. s. for ideal graphite (Soule 1958), is applicable only to ideal graphite, and is rapidly reduced to $\sim 10^3 cm^2$/volt.s. by either disorder or impurity. We adopt for the mobility the value of 4000 cm^2/volt.s. measured by Klein (1962a) for pyrolytic graphite as we do not expect the grains to be quite pure nor to have ideal order.

The use of the concept of mobility, which is a time-averaged effect, is justified as long as the period of oscillation of the effective electric field is much longer than the relaxation time of the carriers in the conduction band. In the case of graphite the relaxation time is of the order of 10^{-12} seconds, so this condition is satisfied.

III. THE POWER SPECTRUM FROM THE ROTATING GRAINS

Classical electromagnetic theory shows that an electric dipole $\underline{p}$ which is time varying in such a way that its second derivative with respect to time is not zero will radiate, the power radiated being given by (see, e.g. Cheston 1964)

$$\frac{2}{3c}\left|\frac{d^2}{dt_o^2}\underline{p}\right|^2 \tag{6}$$

in c.g.s. units, where t_o denotes using the retarded values. This expression is applicable to a dipole which is varying in time but fixed in direction. However, a dipole whose orientation is also a function of time may be replaced, in general, by three linear dipoles, with their moments directed along three fixed mutually perpendicular directions (Born and Wolf 1959). Since our dipoles rotate in a plane we may deal instead with two dipoles pointing in fixed, mutually perpendicular directions, and calculate the second derivatives of these components, adding the results to obtain the power given by equation (6). Let the two component dipoles lie along mutually perpendicular axes OZ and OY which are part of a right hand set O(XYZ) as in Fig. II, and let OZ be coincident with the t = O axis of the grain. Then the component dipoles are

$$p_1 = \tfrac{1}{2}p_o(1-\cos\omega t)\cos\omega t \quad , \quad p_2 = \tfrac{1}{2}p_o(1-\cos\omega t)\sin\omega t. \tag{7}$$

We are concerned with calculating the power radiated from this system at a general point P defined by spherical polar angles (θ_1, φ_1), OZ being the polar axis as shown. From dipole p_1 on axis OZ then the dominant fields are (Born and Wolf 1959)

$$E_{\theta_1} \sim H_{\varphi_1} = \frac{p_1''}{cR} \sin \theta_1 \tag{8a}$$

where p_1'' denotes $\frac{d^2}{dt_o^2} p_1$; and similarly from dipole p_2 on axis OY the fields are

$$E_{\theta_2} \sim H_{\varphi_2} = \frac{p_2''}{cR} \sin \theta_2 \tag{8b}$$

where θ_2 is given by the spherical polar coordinates (θ_2, φ_2) of point P referred to OY as polar axis.

At the sample point P the interference of the two wave trains is measured by $\underline{E}_{\theta_1} \cdot \underline{E}_{\theta_2}$, and in the calculation of the power output we integrate this term over all angles. It is easily seen from Fig. II that if β is the angle between $\underline{E}_{\theta_1}$ and $\underline{E}_{\theta_2}$ then

$$\cos \beta = - \frac{\sin \varphi_1}{(1 + \cos^2\theta_1 \cot^2\varphi_1)^{1/2}} \tag{9}$$

The angular part of the integration may then be shown to be zero.

Hence the total power will be given by the sum of the integrals over a large sphere of the Poynting vectors $\underline{S}_1$ and $\underline{S}_2$ from each dipole, i.e.

$$\text{Power} = \int_{\text{sphere}} (S_1 + S_2) R^2 \sin\theta \, d\theta \, d\varphi \tag{10}$$

where

$$S_1 = \frac{c}{4\pi} E_{\theta_1} H_{\varphi_1} = \frac{p_1''^2}{4\pi c R^2} \sin^2 \theta_1 . \tag{11}$$

Substituting from equation (7) into (11) we obtain for the power

$$\frac{2\omega^4}{3c}\left[5 - 4\cos\omega t\right]\left(\frac{p_0}{2}\right)^2 ; \tag{12}$$

then averaging the power given by (12) over a complete rotation of the grain, the power is given per rotation of the grain by

$$5 p_0^2 \omega^4 / 6c . \tag{13}$$

Expression (12) shows that the radiation is periodic, with frequency ν given by $2\pi\nu = \omega$.

We are concerned with calculating intensity of radiation from all grains in a specified frequency range ν, $\nu + d\nu$. To do this we must take account of the distribution of sizes of the grains and also of the distribution of angular velocity among grains of the same radius.

Let the total number of grains of all radii be N per cm^3. These grains are distributed in radii so that $f(r)\,dr$ is the number with radii between r and r + dr.
Obviously,

$$\int_0^\infty f(r)\,dr = N. \tag{14}$$

Stecher and Donn (1965) have found that the Oort-van de Hulst size distribution originally proposed for ice grains gives a satisfactory representation of interstellar extinction for graphite spheres. We therefore set

$$f(r) = f(0) \exp\left\{-\left(\frac{r}{r'}\right)^{2\cdot 6}\right\} \tag{15}$$

where $r^1 = 6 \times 10^{-6}$ cm. Normalizing (15) with (14) gives

$$f(0) = 1{\cdot}92 \times 10^5 N . \tag{16}$$

Let us suppose that the number of grains with radii between r and r + dr which have angular velocities between

ω and $\omega + d\omega$ is $n_r(\omega)d\omega dr$. Obviously

$$\int_{all\ \omega} n_r(\omega)\, d\omega\, dr = f(r)\, dr. \tag{17}$$

As mentioned in Section II the angular velocity of the grains is controlled, under the condition of equipartition, by the temperature of the gas. However, there will be a Boltzman distribution of angular velocities about the mean value determined by equation (1). Writing down a Boltzman distribution for the angular velocity and normalizing by equation (17) we find

$$n_r(\omega)d\omega\, dr = \sqrt{\frac{2}{\pi}}\, f(r)\left(\frac{I}{kT}\right)^{3/2}\omega^2 \exp\left(-\frac{I\omega^2}{2kT}\right) d\omega\, dr. \tag{18}$$

The total power radiated per rotation from all grains at all frequencies can now be written down: it is

$$\iint_{\substack{all\ r\\ all\ \omega}} n_r(\omega)\ 5p_0^2\omega^4/6c\ d\omega\, dr. \tag{19}$$

Since we are interested in the power radiated as a function of frequency we do not carry out the integration in (19) over ω, only over r. Remembering that $d\omega = 2\pi d\nu$ we may now choose $d\nu$ to be 1 c/s so that the resulting expression is the power radiated by all the grains per cycle per second. It is:

$$\int_0^{\infty} 2\pi\sqrt{\frac{2}{\pi}}\, f(r)\left(\frac{I}{kT}\right)^{3/2}\omega^2 \exp\left(-\frac{I\omega^2}{2kT}\right) 5p_0^2\omega^4/6c\ dr. \tag{20}$$

Recalling the arguments mentioned in II concerning the size and shape of the graphite grains, it is realized that we are concerned only with the tail of the distribution described by equation (15). We therefore replace f(r) in the expression (20) by $\overline{f(r)}$, a suitable average value for the larger particles, introducing a parameter β such that $\beta = \overline{f(r)}/f(0)$.

These arguments also concern the analytic form we choose for the moment of inertia I. For a plate of standard thickness I varies as r^4, and for a sphere $I \sim r^5$. If, as has been suggested, the thickness of the plate is a slowly varying function of the radius then $I \sim r^n$ where n is a parameter between 4 and 5. In view of the uncertainty here, we choose to leave n unspecified. Writing

$$I = L r^n \,, \quad p_0 = M r^m / \omega$$

(20) becomes

$$\sqrt{8\pi}\ \beta\ f(0) \left(\frac{L}{kT}\right)^{3/2} \frac{5M^2\omega^4}{6c} \int_0^\infty r^{\frac{3n}{2}+2m} \exp\left(-\frac{L r^n \omega^2}{2kT}\right) dr$$

$$= \sqrt{8\pi}\ \beta\ f(0) \left(\frac{L}{kT}\right)^{3/2} \frac{5M^2}{6c}\, \omega^4 \left(\frac{L\omega^2}{2kT}\right)^{-\frac{1}{n}\left(\frac{3n}{2}+2m+1\right)} \frac{1}{n} \Gamma\left(\frac{\frac{3n}{2}+2m+1}{n}\right) \qquad (21)$$

where Γ is the gamma function. Expression (21) represents the power in ergs sec^{-1} cm^{-3} $(c/s)^{-1}$ radiated by the grains.

IV. ASTRONOMICAL APPLICATIONS

It is the purpose of this section to show that by assigning credible values to the parameters in expression (21) the characteristics of the galactic non-thermal radio noise can be reproduced. These characteristics are the spectral index and intensity, and they are determined principally by our choice of m and n. The procedure we adopt is to give values to as many parameters as possible, expressing the radio intensity in terms of $V_\perp$, B, ω, T, the path length l, and the parameters m and n. Then m and n may be chosen to give the observed spectral index and the resulting expression for intensity in terms of $V_\perp$, B, 1, T compared with observation.

We choose the following values: $N = 3 \times 10^{-11}$ cm^{-3}, $\beta = 10^{-2}$, $b = 10^{-6}$ cm, and $L = 3$ gm cm^{-3}. By referring to Fig. III we see that of six possible orientations only two are in a position relative to the induced electric field to give a changing dipole moment. In the notation of the figure, these are 2 and 5. This result will also be true in the general case when the orientations of the grains are random, and so in (21) we shall use not N but $\frac{1}{3}$N. Expression (21) gives the intensity in ergs sec^{-1} cm^{-2} (c/s)$^{-1}$ as

$$1{\cdot}1 \times 10^{-19} \left(\frac{L}{2k}\right)^{-2\frac{m}{n}-\frac{1}{n}} \frac{1}{n} \Gamma\left(\frac{\frac{3}{2}n+2m+1}{n}\right) V_\perp^2 B^2 \omega^{1-4\frac{m}{n}-\frac{2}{n}} T^{\frac{2m}{n}+\frac{1}{n}} . \qquad (22)$$

We now identify the spectral index of $1-4\frac{m}{n} - \frac{2}{n}$ with the observed value of -0.6. Pairs of values of m and n which can satisfy this requirement are $n = 4$, $m = 1.2$; $n = 4.5$, $m = 1.3$; $n = 5$, $m = 1.5$. The last pair of values is in best agreement with the arguments expressed in Section II, and we shall adopt these values for m and n. We then have as the intensity

$$3{\cdot}7 \times 10^{-33} V_\perp^2 B^2 \omega^{0{\cdot}6} T^{0{\cdot}8} \, l \quad \text{ergs s}^{-1} \text{cm}^{-2} (\text{c/s})^{-1} . \qquad (23)$$

After the choice of spectral index, the selection of a pair of m, n values has little effect on (23), a variation of ~ 20% appearing because of the term $\frac{1}{n} \Gamma$.

Allen (1963) quotes the intensity at 100 Mc/s measured in the galactic plane as 3.8×10^{-17} ergs sec^{-1} cm^{-2} sterad^{-1}. Assuming the grains are responsible for the radiation at this frequency we have

$$V_\perp^2 B^2 l \; T^{0{\cdot}8} = 2{\cdot}4 \times 10^{22} . \qquad (24)$$

In the plane of the galaxy there are two typical temperatures for the interstellar medium, associated with HI and HII regions. These temperatures are around $100^{o}K$ and $10{,}000^{o}K$ respectively. However, the HII regions are relatively small and if they do radiate will form localized sources. In this calculation we are concerned only with the general background radio-emission. Substituting in (24) a path length l of 10 kpc typical for the galactic plane, and a temperature of $100^{o}K$ we find $V_{\perp} B = \frac{1}{2}$. This means that for a field of 10^{-6} gauss, if the grains have a velocity of a few kilometers a second across the field then the process will work. A field of this size is too small by an order of magnitude to dominate the motion of the interstellar clouds, and so it seems quite reasonable to expect that the grains, as part of an interstellar cloud, will have velocities of kilometers a second across the field lines.

We have shown that assigning credible values to the various parameters indicates that graphite grains could be the source of the galactic non-thermal radiation. We must also ask if the process will run down allowing for the fact that the energy of radiation has its source in the translation of the grain across the field. There are two possible mechanisms. First, the radiation pressure as the radio photon is emitted will tend to slow down the rotation of the grain; however, this process can easily be shown to be negligible. Second, the rotation can be slowed by currents induced by the extra electric field given by the second term in equation (2). This situation has been treated by Rosenstock (1956) in considering the motion of an artificial satellite in the earth's magnetic field. An application of this theory to the grains shows that the rate of slov[illegible] is negligible. The conclusion is, therefore, that the grains will be maintained in rotation by thermal equilibrium and that the process described here should produce the radio noise. It must be pointed out that in principle the parameters m and n should be available from interstellar optical polarization and extinction measurements. Further work in these fields is required before such deductions are possible.

The typical spectrum of the galactic radio noise has, as we have discussed, a spectral index of - 0.6 at frequencies of about 100 Mc/s. However, as the frequency decreases the spectral index also decreases and the intensity passes through a maximum at around 10 Mc/s. ~~for the 100°K rotational temperature~~. Below this the intensity falls rapidly. On the model here discussed there is a simple explanation in the fact that there is a range of sizes of flat grains, but that when measurements are made at lower frequencies (which are produced by the larger grains) there are fewer of the large grains, so that the intensity falls off. Again, when from optical measurements some clearer idea of the size distribution is obtained this intensity diminution may readily be calculated.

Finally, it should be noted that though we have applied this mechanism only to the background galactic non-thermal radiation, it must obviously be considered for localized sources as well. Although higher number densities of relativistic electrons than grains may be possible, the intensity of the grain mechanism increases as a function of magnetic field faster than the synchrotron mechanism and so may dominate in high field conditions. Radiation from a single oscillating dipole is fully polarized, so the radio-emission from our grains should exhibit some degree of polarization.

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Legends for the Figures

Figure I

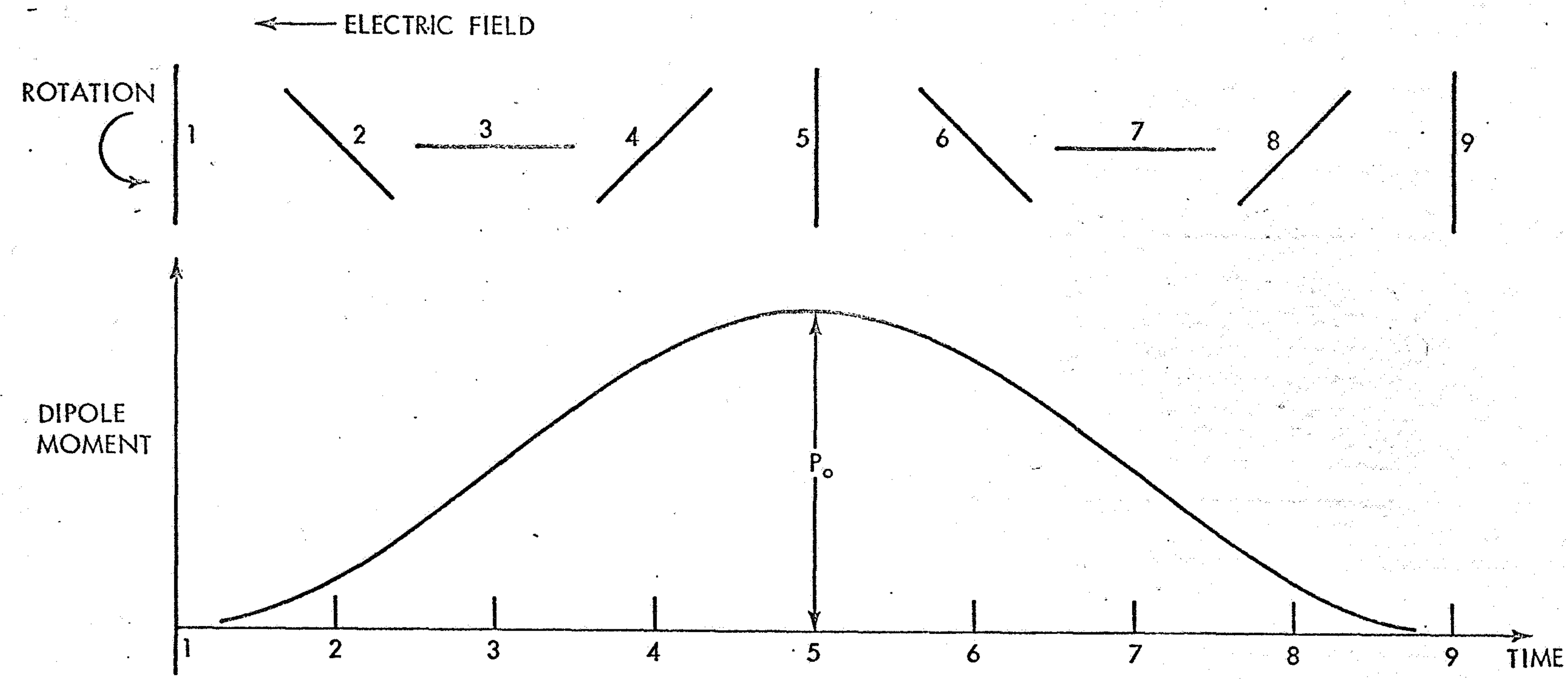
(a) is a representation of the instantaneous orientations of the rod as it rotates, and (b) gives the relative induced electric dipole moment corresponding to any position during the rotation. (c) represents by the intercept on the cardioid the change in magnitude of the induced dipole moment, as the orientation of the rod represented by the radius vector changes in the cycle of rotation of the rod.

Figure II

The sample point P is located with respect to the rectangular axes O(XYZ) by the spherical polar angles (θ_1, φ_1) where OZ is the polar axis. From the component dipole p_1 lying along OZ the resultant dominate electric field is E_{θ_1} as shown. A component dipole p_2 lying along OY gives an electric field E_{θ_2}, where (θ_2, φ_2) are the angles defining P relative to the axes O(XYZ), OY being regarded as the polar axis.

Figure III

An idealization of the modes of rotation of the grain. Of the siz possible idealized modes only those labelled (2) and (5) possess an oscillating dipole moment.


ELECTRIC FIELD
ROTATION
1
2
3
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8
9
DIPOLE MOMENT
P₀
1
2
3
4
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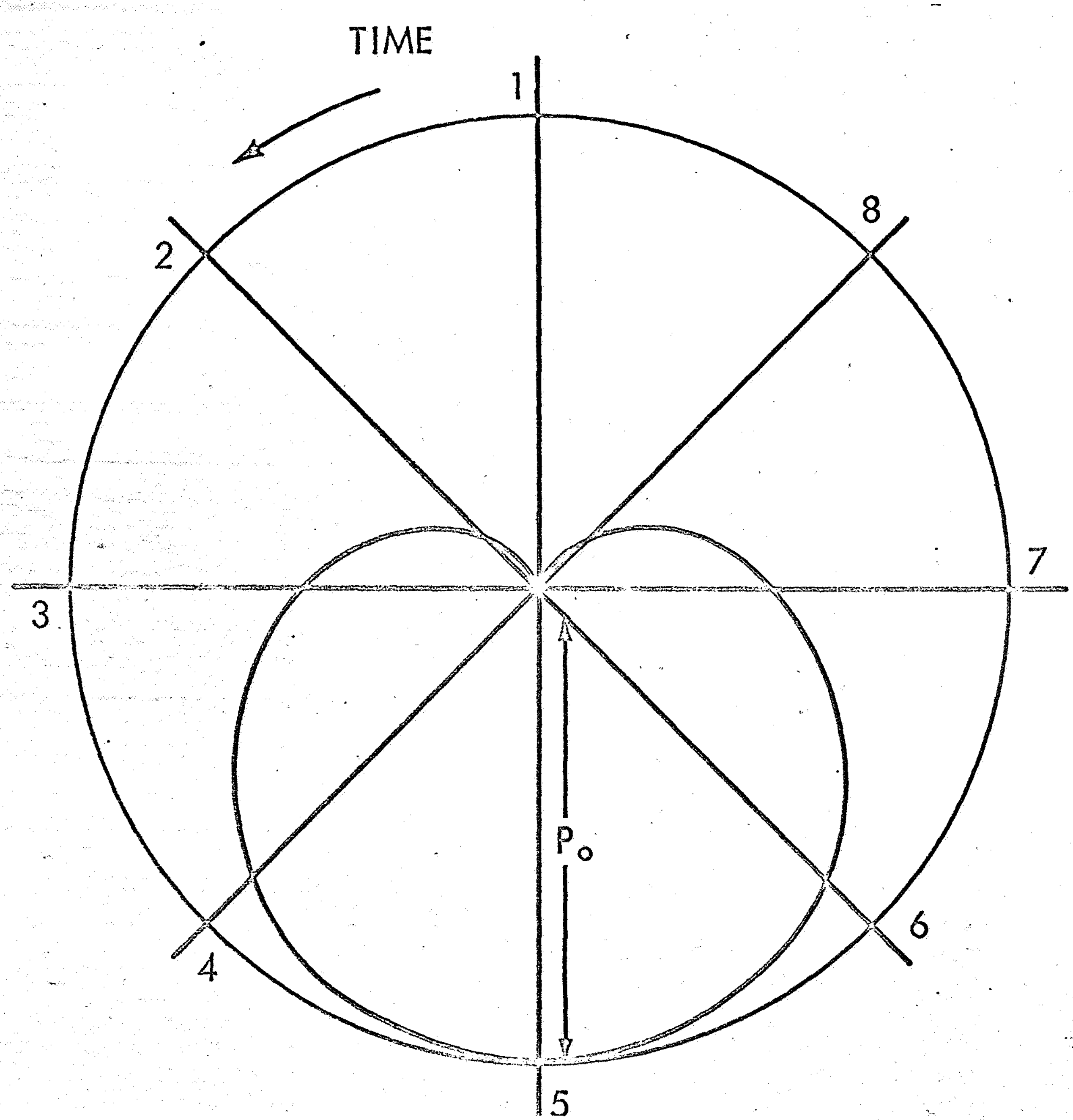
TIME



TIME
1
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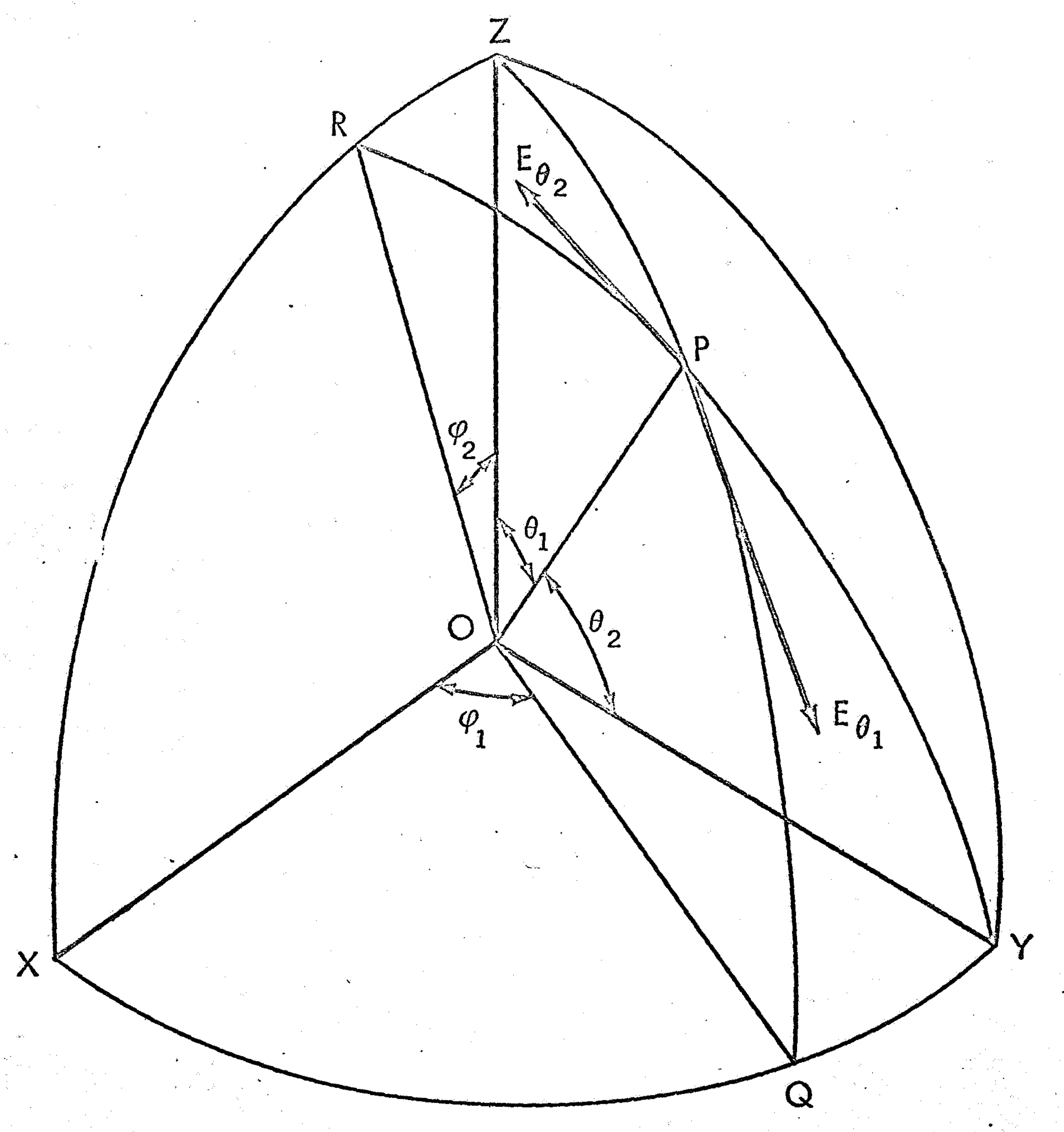
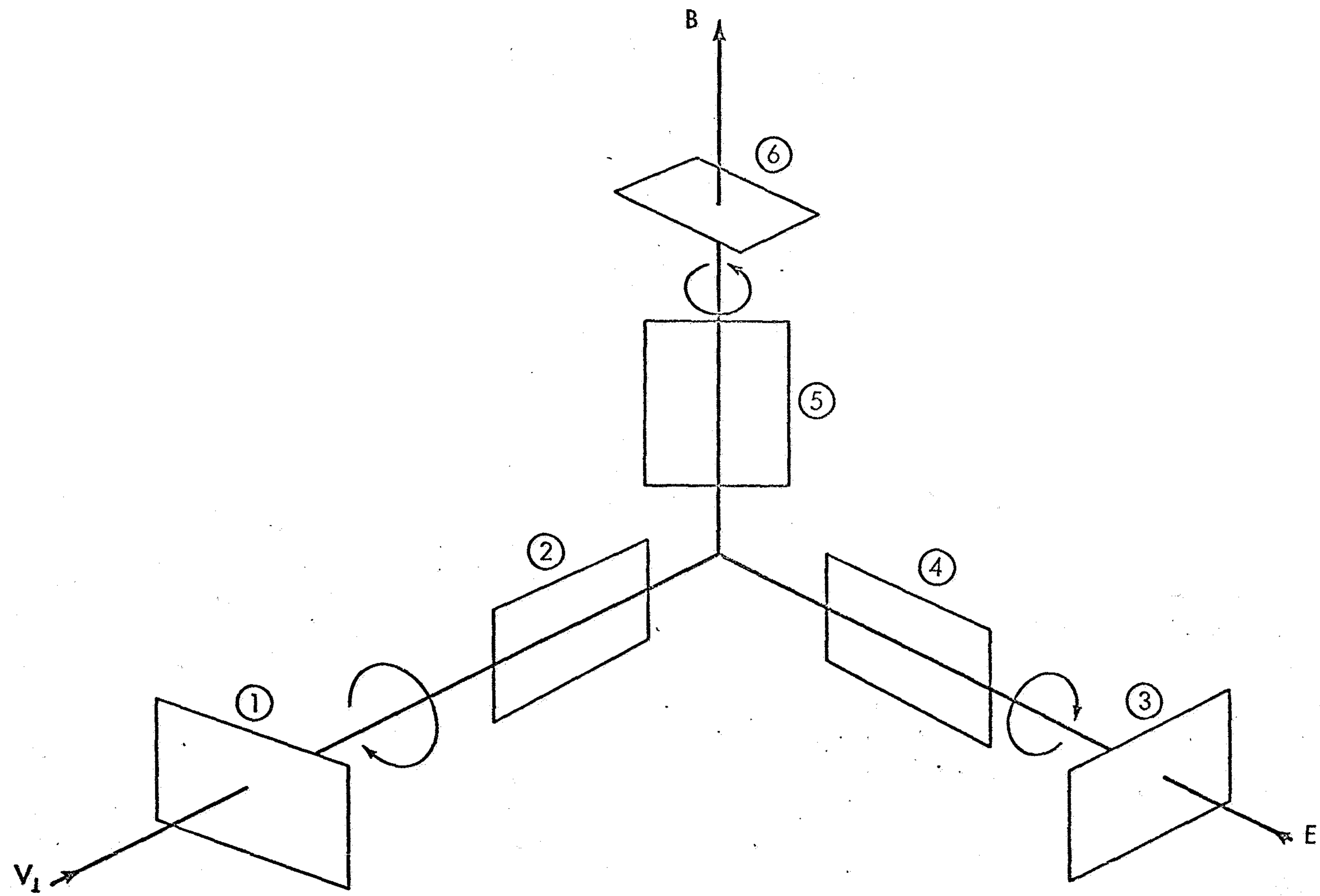
7
8
P_o


Z
R
E_{θ_2}
P
φ_2
θ_1
O
θ_2
φ_1
E_{θ_1}
X
Y
Q


B
6
5
2
4
1
3
V1
E